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(71) Applicant: IBM DEUTSCHLAND GMBH
Pascalstrasse 100
D-7000 Stuttgart 80(DE)

(84) DE

(71) Applicant: International Business Machines Corporation
Old Orchard Road
Armonk, N.Y. 10504(US)

(84) FR GB

(72) Inventor: Järisch, W., Dr.
Finkenweg 15
D-7030 Böblingen(DE)
Inventor: Makosch, G.
Stuttgarter Strasse 40
D-7032 Sindelfingen-Maichingen(DE)

(74) Representative: Mönig, Anton, Dipl.-Ing. et al
IBM Deutschland GmbH Schönaicher Strasse 220
D-7030 Böblingen(DE)

(54) Phase-sensitive interferometric mask-wafer alignment.

(57) In an alignment method for lithographic devices of the proximity printing type two light beams (9a,d;9b,c) are made to impinge symmetrically on gratings (3) associated to each alignment direction on mask (1) and wafer (2) such that diffracted beams return along the optical axis of the alignment system. The relative phase of the diffracted beams is measured with a phase compensation technique using an electro-optic modulator (15). The alignment method is performed in two steps, the first being a normalizing step where a smooth portion of the wafer is brought under the alignment grating in the fixed mask (2) and a measuring step yielding the phase difference as a position control signal when the alignment grating on the wafer has been brought under the alignment grating of the mask. The four partial beams required for alignment in two orthogonal directions are generated from a single laser beam (15) in a compact set (14) of birefringent crystals or Wollaston plates and half-wave retarders.

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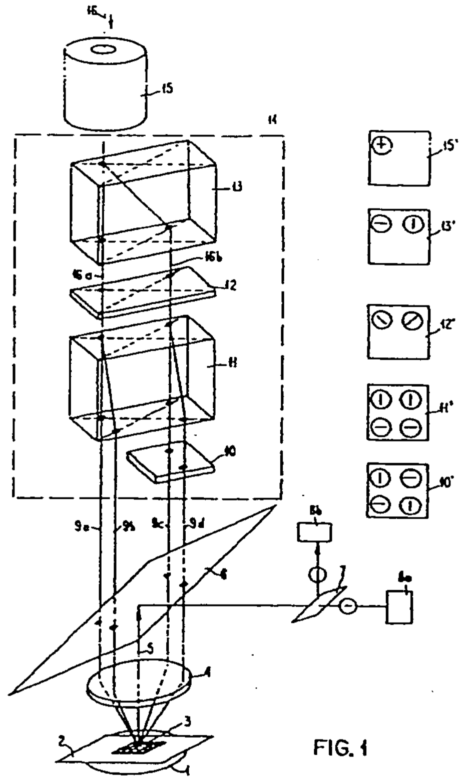

FIG. 1

PHASE-SENSITIVE INTERFEROMETRIC MASK-WAFER ALIGNMENT

Field of the Invention

The invention relates to a method and an apparatus for aligning two parallel objects in different planes, in particular a mask with respect to a wafer in lithographic systems, preferably of the proximity printing type using corpuscular beams or X-rays. A novel optical beam separation device used in such an apparatus can be applied in other optical devices as well.

Background of the Invention

In the manufacture of integrated circuits by lithographic methods exposure masks must be aligned (or registered) relative to structures on the wafer with an accuracy that is only a fraction of the smallest structural detail in the mask; in present photolithographic methods with smallest line widths in the order of 1 µm alignment accuracies of 0,3 µm can be achieved with manual or automatic alignment methods using suitably shaped alignment marks on mask and wafer.

The further decrease of line width to some tenths of a micrometer which is expected from corpuscular beam and X-ray lithography over the next years will thus require alignment accuracies in the order of nanometers. Additionally, alignment must be performed in short times (typically less than a second) for high throughput in the production line, in particular when large wafers are exposed in the step- and repeat-mode where each position requires its own alignment. Conventional visual methods cannot meet these requirements for accuracy and speed.

One approach that has been discussed in the art to achieve high accuracy uses optical gratings as registration marks on mask and wafer and derives the registration control signal from light diffracted at these gratings. Accuracies in the nanometer range can then be achieved if the evaluation process is based on phase sensitive methods as described in European Patent Publication No. 45321 or in the article by G. Makosch, B. Solf "Surface Profiling by Electro-optical Phase Measurement", Proc. Soc. Photo-opt. Instrum. Eng. 42,316(1981). This prior system is, however, conceived for photolithographic printers of the projection type where an optical imaging system is interposed between mask and wafer; it thus cannot be used in proximity printing systems with masks-wafer separations in the order between 50 and 100 µm.

Alignment techniques using optical gratings on mask and wafer in an x-ray exposure system of the proximity printing type have been described by A. Une et al. in Bull, Japan Soc. of Prec. Engg., Vol. 19, No. 1, March 1985) page 71: "A highly accurate alignment technique using a dual grating" and by J. Ito and T. Kajamana in Japanese Journal of Applied Physics, Vol. 25, No. 6, June 1986, page L487-L489 "A new interferometric displacement-detection method for mask to wafer alignment using symmetrically arranged three gratings". These techniques evaluate the intensities of different diffraction orders and might therefore encounter difficulties in practical use when the wafer is covered with various layers in different processing steps that may change the reflectivity and give rise to interference effects disturbing the measured intensity.

Summary of the Invention

It is therefore the object of the present invention to provide an improved alignment method and apparatus, in particular for lithographic systems of the proximity printing type, which yield alignment accuracies in the nanometer range, can be performed with high speed and in automated operation and which is insensitive to intensity variations of the diffracted light.

This object is achieved by the invention as recited in the claims 1 and 6; embodiments of the invention are characterized in the dependent claims. Novel beam splitters usable in the alignment apparatus are defined in claims 7 and 8.

Briefly, the method according to the invention is based on an interferometric technique which measures the phase shift of a light wave after diffraction at a grating. This phase shift is proportional to the lateral displacement of the grating and can be determined with great precision by introducing a compensating phase shift in an electro-optic crystal.

In the first (or gauging) step of the method according to the invention the phase of the light wave is determined with the spatially fixed grating in the mask being located over a blank area of the wafer. The second phase measurement is taken when the wafer alignment grating has been brought into near alignment to the mask (deviation less than g/4, g being the grating constant); the alignment or position control signal is then the relative phase difference between the two measurements.

The gratings on mask and wafer can be linear gratings if alignment is to be performed for one

coordinate direction only or crossed gratings for simultaneous alignment in x- and y-direction.

An apparatus to carry out alignment in two dimensions uses an arrangement of birefringent or Wollaston crystals that generate the required four parallel partial beams with polarization directions appropriate for phase sensitive signal evaluation. This beam splitting arrangement can be used in other optical systems as well where four parallel partial beams are required; one field of application is in optical distortion testers for photolithographic masks.

Brief Description of the Drawings

Fig. 1 shows a schematic diagram of the optical alignment system in accordance with the invention;

Figs. 2A, B show the relative position of mask and wafer when the first and the measurement step, resp., of the alignment method in accordance with the invention is performed;

Figs. 3A, B show schematic diagrams of the incident and the diffracted beams in the two measurement steps of the alignment method according to the invention;

Figs. 4A,B,C show schematic vector diagrams to indicate the phase relationship between the beams of Figs. 3

Fig. 5 shows an alternate embodiment of the optical alignment system in accordance with the invention.

Preferred Embodiment of the Invention

Fig. 1 shows a schematic drawing of a novel optical system that can be used to carry out the method of the invention.

A wafer 1 is mounted on a x, y-stage for exposure in the step- and repeat mode through mask 2 which is held stationary with respect to the exposing beam and parallel to wafer 1 with a separation in the order between 20 and 100 µm. The exposing beams may be light, X-rays or corpuscular beams. Wafer 1 is covered with a photoresist layer and in most cases with other layers applied in previous manufacturing steps. Before each exposure wafer 1 must be controllably displaced for alignment with the fixed mask, e.g. by accurate micromanipulators. For mask 2 and each area of wafer 1 onto which the shadow of mask 2 is to be projected in the proximity printing process the invention proposes gratings 3 as registration marks. In case of one-dimensional alignment linear gratings are used which are parallel to each other on mask and wafer; in case of two-dimensional alignment crossed gratings are provided. The grating constant g is typically in the order of 10 µm to achieve the desired alignment accuracy in the nm-range.

Before interferometric alignment according to the invention is performed, wafer 1 has to be aligned to its nominal position within g/4, e.g. within an accuracy in the µm-range. This is easily achievable with conventional methods, e.g. by displacing the interferometer controlled x, y-stage on which wafer 1 is mounted.

For the alignment method of the invention grating 3 on the mask is symmetrically illuminated by two pairs of light beams 9a, 9d, and 9b, 9c, respectively, each of which spans a plane that is perpendicular to the plane of the other pair. All beams are linearly polarized, the equal polarization directions in one pair being perpendicular to the polarization of the other beam pair. A lens 4 focusses beams 9 onto grating 3; focal length and grating constant are chosen such that the diffracted beams 5 return along the optical axis of lens 4 to be deflected by semi-transparent mirror 6 onto a polarizing beam splitter 7 which separates the mutually orthogonal polarization directions of the diffracted beams to detectors 8a, 8b, respectively.

Beams 9 are generated from a linearly polarized laser beam 16 which traverses an electro-optical phase modulator 15, where two colinear, partial beams with mutually orthogonal polarization directions are created. The polarized beams enter an optical beam separation arrangement 14 with a calcite crystal 13 to be spatially separated into partial beams 16a, 16b. (The polarization directions are symbolically indicated on the right of Fig. 1, where reference numeral 15′ shows the unseparated polarized beams at the exit of modulator 15, reference numberal 13′ the separated beams at the exit of calcite crystal 13 and so on.)

Partial beams 16a, 16b then pass quarter-wave retardation plate 12 which rotates the polarization directions by 45° for further spatial splitting in calcite crystal 11 having the same length as crystal 13. At the exit of crystal 11 four partial beams 9 are available, two of which pass a half-wave retardation plate 10 to rotate their polarization directions by 90°. The resulting partial beams 9a - 9d are therefore arranged at the corners of a square 10′ such that diagonal beams (e.g. 9a,9d) have the same direction of 10′ polarization perpendicular to the polarization of the beam pair (9b,9c) on the other diagonal. Activation of modulator 15 will thus modulate the phase difference within each pair of diagonal beams.

In this arrangement the two beams diffracted at one set of parallel bars in the crossed grating 3 will thus have a polarization different from those reflected at the orthogonal sets of bars and can be

separated by polarizing beam splitter 7 as indicated by the polarization symbols in the beam paths of Fig. 1. Measuring the phase of the light beams received by detectors 8a, 8b yields the desired alignment control signals as it will now be explained in detail. The method to measure the phase is known in itself and described e.g. in the above-noted article by Makosch/Solf; it is based on compensating the diffraction introduced phase shift by periodically modulating electro-optic crystal 15.

The alignment method of the invention is carried out in two steps:

Step 1 (Fig. 2A): A blank (or unstructured) part 1a, e.g. a kerf zone of wafer 1, is brought under alignment grating 3a of mask 2 before the mask grating is symmetrically illuminated by partial beams 9a,9d (in the one-dimensional case shown in Fig. 2). The phase of diffracted beam 6 travelling along the optical axis is then determined by electro-optic modulation to serve as reference value (preferably set to zero) for the actual measurement step of Fig. 2b.

Step 2 (Fig.2B): Alignment grating 3b on wafer 1 is brought under mask grating 3a with an accuracy of better than +/- g/4 before the phase of diffracted beam 6 is measured again. This second phase measurement represents the misalignment such that alignment is to be continued until a phase difference of zero is measured in this second step.

Figs. 3A and B show in greater detail the diffracted beams which are generated in the above described two measurement steps; Figs. 4A-C show vector diagrams to illustrate the phase relationship between these beams.

The symmetrically incident beams S_1, S_2 with the same polarization direction are first reflected at mask grating 3a, whereby two diffracted beams as S_{11}, S_{21} appear; then the incident beams are reflected at blank wafer 1 to pass grating 3a in transmission whereby two further diffracted beams S_{12} and S_{22} appear. In complex notation these diffracted beams are expressed as follows:

$$S_{11} = A \exp(i(P_{GM} + P/2))$$

$$S_{12} = B \exp(iP_h) \exp(i(P_{GM} + P/2))$$

$$S_{21} = A \exp(-i(P_{GM} + P/2))$$

$$S_{22} = B \exp(iP_h) \exp(-i(P_{GM} + P/2))$$

where

A, B = amplitude of the incident beams

P_{GM} = phase shift due to the lateral displacement ΔX of mask grating: $P_{GM} = 2\pi\Delta X/g$

P_h = phase shift due to air-gap h between mask and wafer:

$P_h = 4\pi h\cos\alpha/\lambda$

P = phase shift in phase modulator.

Fig. 4A represents the vectors of the individual beams present in step 1 of the aligning method; the phase shift P introduced by the modulator has been set to P = 0 for the sake of simplicity.

The two resultants S_1', S_2' represent the superposition of the first diffraction orders generated from incident beam S_1 and S_2, respectively; other diffraction orders may be chosen as well. The angular difference $2P_{GM}$ between the resultants S_1', S_2' is measured with the above-mentioned phase compensation method.

Superposition of these diffracted beams (which all have the same polarization direction) yields the output beam S (reference numeral 6 in Fig.1)

$S = S_{11} + S_{12} + S_{21} + S_{22}$

$= 2\cos(P_{GM} + P/2)\,(A + B\exp(iP_h))$

The intensity of the output beam 6 is thus:

$J = |S|^2 = 2\,(A^2 + B^2 + 2AB\cos P_h)\,(1 + \cos(2P_{GM} + P))$

This equation represents a harmonic function whose amplitude varies with the distance between mask and wafer; the phase term $2P_{GM}$ represents the lateral displacement ΔX of the mask acccording to

$$P_{GM} = 2\pi \cdot \frac{\Delta X}{g}$$

It is to be noted that this phase shift P_{GM} is independent of the mask-wafer separation h; this is in contrast to alignment methods based on the evaluation of the diffracted amplitude J which is indeed dependent on h!

After the blank wafer surface of measurement step 1 has been replaced by wafer alignment grating 3b (Fig.3B) two additional orders of diffraction s_{13} and s_{23} are generated and introduce an additional phase shift; the phase difference measured in step 1 is therefore changed if mask and wafer are not exactly aligned relative to each other.

Fig. 4B shows how the diagram of Fig. 4A is modified after the blank wafer area 1a has been replaced by the wafer grating area 3b, and if the new diffraction orders generated by the wafer grating are <u>not</u> yet considered. The amplitude of the diffracted beams S_{12} and S_{22} is decreased such that S_1' and S_2' of Fig. 4A are rotated without a change in their angular distance $2P_{GM}$ into vectors S_1'' and S_2''.

In complex rotation, the diffracted beams are then expressed as:

$S_{12}' = B' \exp(iP_h) \exp(iP_{GM})$

$S_{22}' = B' \exp(iP_h) \exp(-iP_{GM})$

Fig. 4C represents the final vector diagram in which the additional beams S_{13} and S_{23} diffracted at mask grating 3a are considered. They are expressed as:

$S_{13} = C \exp(iP_{h1}) \exp(iP_{WM})$

$S_{23} = C \exp(iP_{h1}) \exp(-iP_{WM})$

where

P_{h1} = phase shift of new diffracted beam due to air gap h

P_{WM} = phase shift introduced by lateral displacement of wafer grating 3b

The new resultants are now S_1'' and S_2'' with an angular distance 2 P_{GWM} which is measurable by the phase compensation method.

The measurable phase angle (P_{GM} in step 1 and P_{GWM}in step 2 of the proposed method) are only identical, if the mask displacement coincides with the wafer displacement; the value of P_{GM} is used as a reference value (and set to zero) so that in the alignment process P_{GWM} has to be adjusted to zero as well.

The measured phase angle P_{GWM} in step 2 therefore represents a measure for alignment deviations between mask and wafer; the relationship, is however, not linear, as can be shown by calculating the intensity of the superimposed means shown in Fig 4C. The measured light intensity J can then be expressed as

$J = E + F \cos^2 (P_{GWM} + P/2)$

The continuously measured phase angle P_{GWM} is identical to P_{GM} only if the alignment condition $P_{GM} = P_{GWM}$ has been achieved by suitable displacement of the wafer.

Fig. 5 shows another embodiment of a beam-splitter arrangement 14′ that generates two pairs of beams, such that the beams in each pair have the same polarization direction perpendicular to the beams in the other pair and span one of two orthogonal planes. The output beam of modulator 15 is focussed on a first Wollaston prism 50 to be split symmetrically into beams with perpendicular directions of polarizations which are then rotated by 45 degrees in λ/4- plate 51. A lens 52 focusses the divergent beams onto a second Wollaston prism 53, which is crossed with respect to the first Wollaston prism 50 and generates four symmetrical beams impinging on a second collimating lens 54. Half-wave retardation plate 10 rotates the polarization direction of the left-hand beams in Fig. 5 to provide the desired polarization pattern in the four beams.

The other elements of Fig. 5 correspond to those of Fig. 1 and carry the same reference numerals. The polarization directions of the beam are indicated in Fig. 5 in the conventional way. The symmetry of the beam paths in Fig.5 relative to the optical axis makes them easier to adjust.

The beam splitter arrangements 14 in Fig. 1 and 14′ in Fig. 5 can be used in other optical set-ups as well, where four partial beams with selectable polarization directions are required (the relative polarization can be adjusted by appropriate choice of wave retarding plates 10 for individual beams).

The beam splitter arrangements 14, 14′ are particularly suited for an optical distortion tester, as described in European Patent No. 40700, to generate two pairs of polarized beams; these beams are directed via a roof top prism to four separate beam expanders from which they impinge symmetrically on a test object, e.g. a photo mask with grating like patterns. After diffraction the beams return in the direction vertical to the object. For high sensibility high diffraction orders are preferred. In this particular application half-wave plate 10 is composed of two parts with different orientations such that all four partial beams 9a-d have their polarization directions in one plane.

Claims

1. Method for aligning two parallel objects (1,2) in different planes, each object carrying an optical grating to diffract light beams with symmetrical incidence into a direction normal to the surface of the objects, the phase of the diffracted beams being analyzed by electro-optic phase compensation,

characterized in that the following steps are performed in a lithographic system of the proximity printing type:

- determine the phase of the diffracted beams (6) for each alignment direction when the alignment grating (3a) of one object (2) is positioned over a smooth surface of the other object (1),
- determine the phase of the diffracted beams (6) for each alignment direction after the grating (3b) of the second object has been brought under the alignment grating (3a) of the first object with an alignment accuracy of better than g/4, g being the constant of the gratings,
- apply the relative phase of the second measurement step as position control signal to displace one of the objects.

2. The method of claim 1, wherein for each alignment direction one pair of symmetrically incident polarized beams (9a,d;9b,c) is provided, the polarization directions of both pairs being opposite, and wherein the diffracted beams are separated according to their polarization direction for independent alignment measurement in two dimensions.

3. The method of claim 1 or 2, wherein the diffracted beams are of the first diffraction order.

4. The method of one of the claims 1-3, wherein the alignment gratings have equal grating constants in the order of 10 µm.

5. The method of one of the claims 1-4, used in X-ray projection lithography.

6. Apparatus for aligning two parallel objects in different planes, each carrying an identical optical grating (3) as alignment mark, the apparatus comprising:
- an electro-optic modulator (15) to generate two modulated beams with orthogonal polarization from a linearly polarized laser beam (16)
- a beam splitter means (14) generating two pairs of beams (9), each pair (9a,d;9b,c) having the same direction of polarization perpendicular to the polarization of the other pair and spanning a plane that is orthogonal to the plane of the other pair
- means (4) to focus the partial beams symmetrically on a common point on the alignment grating (3)
- diffraction means (6) to direct the diffracted beams (5) to a polarized beam splitter (7) separating the polarization directions to associated detector means (8a,b)
- electro-optic phase evaluation means associated to each detector means (8a,b).

7. A beam splitter means as used in claim 6, comprising in sequence along its optical path:
- a first birefringent crystal (13) to separate a beam of light (16) into two partial beams (16a,16b) with orthogonal polarization directions
- a quarter-wave beam retarder (12) rotating the polarization planes of both partial beams by 45°
- a second birefringent crystal (11) to separate each partial beam into two further partial beams (9a-9d)
- optionally, half- or quarter-wave retarders in the path of selected partial beams.

8. A beam splitter means as used in claim 6, comprising in sequence along its optical path:
a first Wollaston prism (50) to symmetrically separate a beam of light (16) into two partial beams with orthogonal polarization direction
- a quarter-wave beam retarder (51) rotating the polarization planes of both partial beams by 45°
- a first collecting lens (52)
- a second Wollaston prism (53), arranged in the focus of the first lens (52) and crossed with respect to the first Wollaston prism (50), to separate each partial beam into two further partial beams
- a second collecting lens (54) to collimate the partial beams emerging from the second Wollaston prism (53)
- optionally, half or quarter wave retarders in the path of selected partial beams.

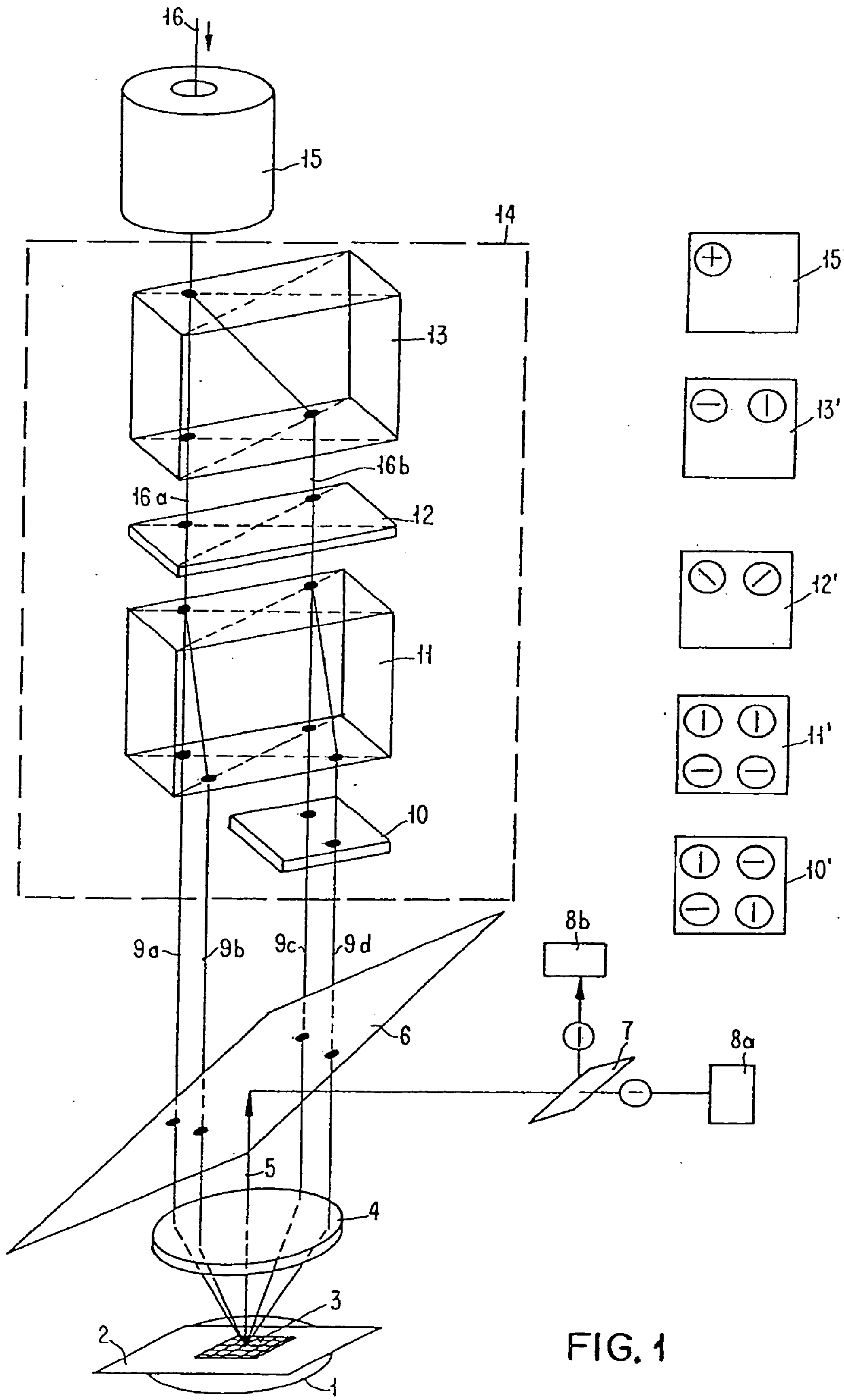

FIG. 1

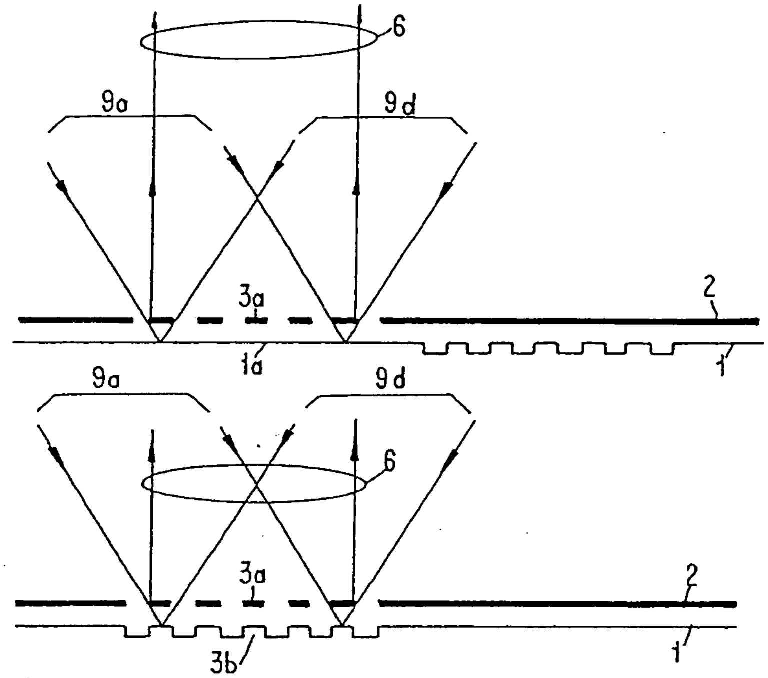

FIG. 2A

FIG. 2B

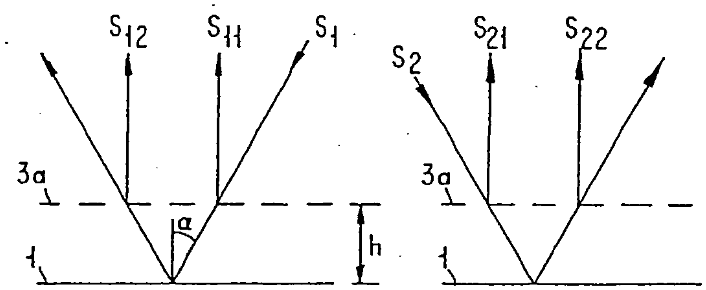

FIG. 3A

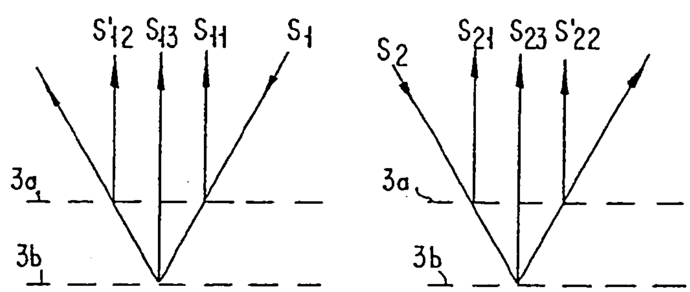

FIG. 3B

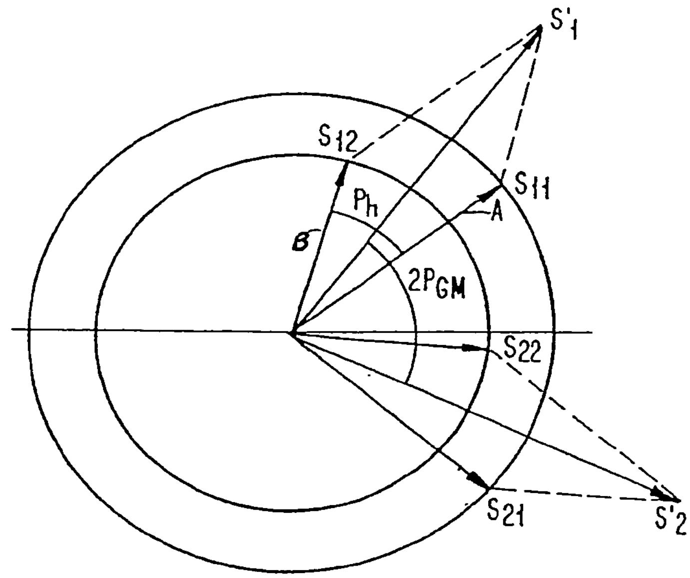

FIG. 4A

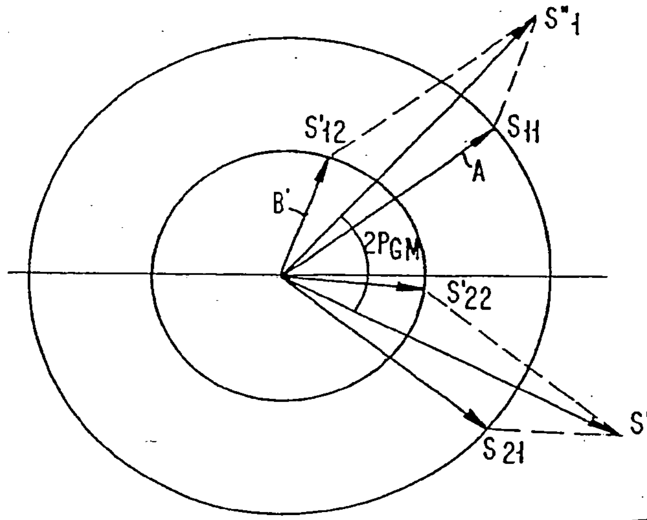

FIG. 4B

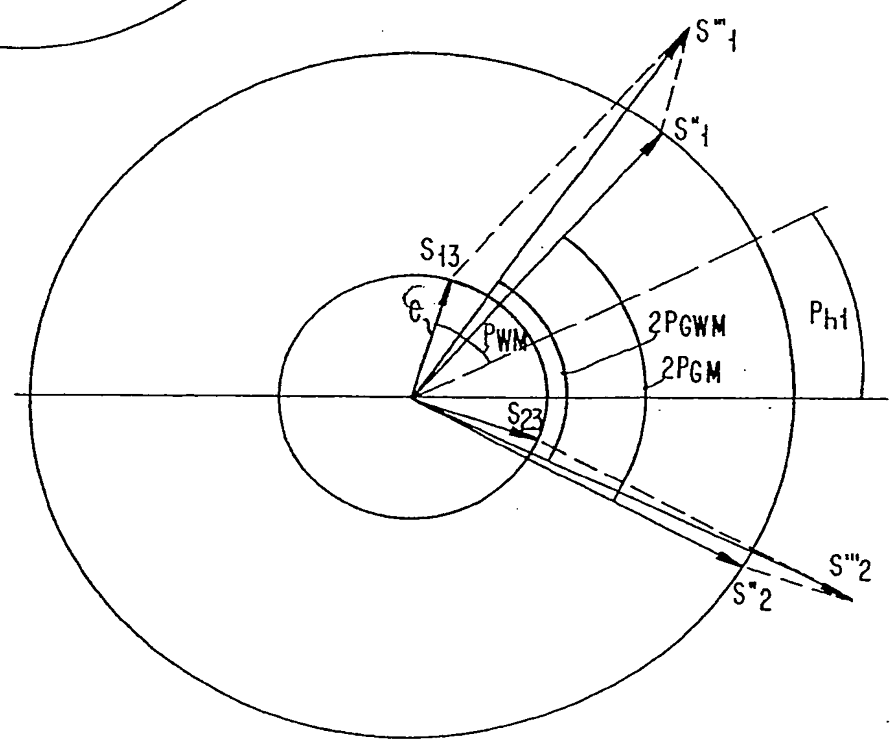

FIG. 4C

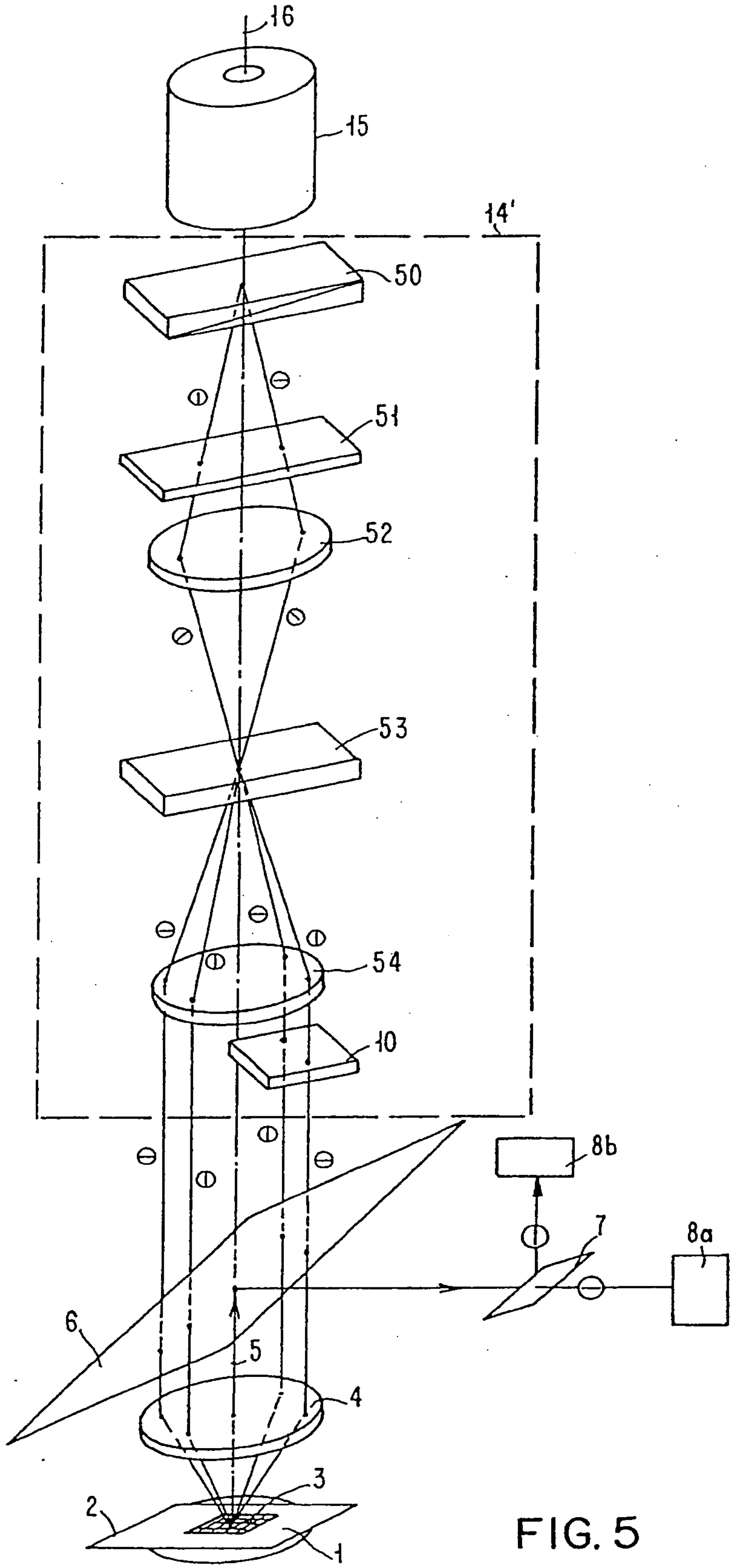

FIG. 5

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EUROPEAN SEARCH REPORT

Application number

EP 87 11 5965

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.4)
A	APPLIED OPTICS, vol. 26, no. 14, July 15, 1987, pages 2823-2835; New York, US G. MAKOSCH et al.: "Phase-locked interferometry for automatic mask alignment in projection printers" * Page 2829, right-hand column, last paragraph; page 2830, left-hand column; figure 1 * --	1,3,4	G 03 F 9/00 G 01 B 11/30 G 02 B 27/28 G 02 B 27/10
A,D	PROC. SOC. PHOTO-OPT. INSTRUM. ENG. vol. 316, 1981, pages 42-53 G. MAKOSCH et al.: "Surface profiling by electro-optical phase measusrements" * Page 44, paragraphs 1,2 * --	1	
A,D	EP-A-0 045 321 (IBM) * Page 1, lines 5-17; page 3, line 31 - page 4, line 10; page 14, lines 1-9; figures 1,4c * --	1,3,4	**TECHNICAL FIELDS SEARCHED (Int. Cl.4)**
A	APPLIED OPTICS, vol. 23, no. 4, February 15, 1984, pages 628-632; New York, US G. MAKOSCH et al.: "Interferometric method for checking the mask alignment precision in the lithographic process" * Page 628, right-hand column, paragraph 2; page 629; page 630, paragraph III, lines 1-10; figures 1,2 * -- ./.	1	G 03 B 41/00 G 03 F 9/00 H 01 J 37/00

Place of search	Date of completion of the search	Examiner
The Hague	11-08-1988	WITH

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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A : technological background
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T : theory or principle underlying the invention
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CLAIMS INCURRING FEES

The present European patent application comprised at the time of filing more than ten claims.

☐ All claims fees have been paid within the prescribed time limit. The present European search report has been drawn up for all claims.

☐ Only part of the claims fees have been paid within the prescribed time limit. The present European search report has been drawn up for the first ten claims and for those claims for which claims fees have been paid,

namely claims:

☐ No claims fees have been paid within the prescribed time limit. The present European search report has been drawn up for the first ten claims.

X LACK OF UNITY OF INVENTION

The Search Division considers that the present European patent application does not comply with the requirement of unity of invention and relates to several inventions or groups of inventions,

namely:

1. Claims 1-5: Method for aligning using two steps to determine relative phase applied as position control signal
2. Claim 6: Apparatus for aligning comprising beam splitter means, electro-optic phase evaluation, etc........
3. Claims 7,8: Beam splitter comprising birefrigent crystal and quarter-wave beam retarder

☐ All further search fees have been paid within the fixed time limit. The present European search report has been drawn up for all claims.

☐ Only part of the further search fees have been paid within the fixed time limit. The present European search report has been drawn up for those parts of the European patent application which relate to the inventions in respect of which search fees have been paid,

namely claims:

☒ None of the further search fees has been paid within the fixed time limit. The present European search report has been drawn up for those parts of the European patent application which relate to the invention first mentioned in the claims,

namely claims: 1-5

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EUROPEAN SEARCH REPORT

Application number

EP 87 11 5965

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int Cl 4)
A	WO-A-85 04 266 (HUGHES AIRCRAFT) * Abstract; figure 1 *	1,5	
A	US-A-4 631 416 (TRUTNA, Jr.) * Abstract; figure 3 *	1	
A	US-A-4 636 626 (HAZAMA et al.) * Abstract; figures 3A,3B,4A,6A *	1,5	
A	US-A-4 656 347 (UNE et al.) * Column 14, line 20 - column 15, line 10; column 17, lines 50-55; column 18, lines 58-62; figures 23,27,31,32 *	1,5	
A	JP-A-61 215 905 (MAGONE et al.) * Abstract; figure 1 * & US-A-4 710 026		TECHNICAL FIELDS SEARCHED (Int. Cl.4)
A	JP-A-62 056 818 (MAGONE et al.) * Abstract; figure 1 * & US-A-4 710 026		

Place of search	Date of completion of the search	Examiner

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X : particularly relevant if taken alone
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T : theory or principle underlying the invention
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